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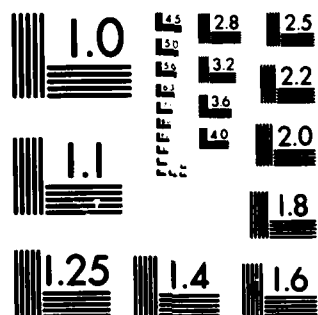
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**TWO WAVELENGTH OPTICAL MULTIPLEXING
SYSTEM FOR ANALOG DATA LINK**

Final Technical Report

28 September 1981 to 30 November 1982

Contract NO0014-81-C-2640

ITT Project No 36058

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Prepared for:

Naval Research Laboratory
Washington, D.C. 20375

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1.0 INTRODUCTION

This final technical report covers the work done on Naval Research Laboratory (NRL) contract N00014-81-C-2640 by ITT Electro-Optical Products Division (EOPD) from 28 September 1981 to 30 November 1982. The objective of this contract was to design, fabricate, deliver, and provide factory measurements for a two-wavelength optical multiplexing system for a fiber optic analog data link. The wavelength division multiplexing (WDM) system consisted of one multiplex coupler and one demultiplex coupler designed to provide codirectional communication channels at wavelengths of 790 nm and 860 nm on 50- μ m/125- μ m core/cladding diameter optical fiber.

The lensed dichroic coupler (LDC) design was used for the system. The LDC is a mature WDM coupler design at ITT EOPD and no major problems were encountered in meeting the channel loss, channel crosstalk, dispersion, and environmental requirements of the contract. For the system composed of the multiplex coupler, a 900-m fiber link, and a demultiplex coupler, maximum coupler channel loss was measured to be 4.1 dB over the 0°C to +50°C range. This low loss was well within the 6.0 dB requirement and essentially met the 4.0 dB goal. Over the same temperature range, crosstalk rejection was about 50 dB in the 860-nm channel and 33 dB in the 790-nm channel. Pulse dispersion was well below the 2.0-ns maximum requirement. A vibration test per MIL-T-5422F(AS) and an NRL-specified shock test were passed.

Section 2.0 of this final technical report documents the coupler optical design, the coupler package design. and the fiber/cable type used. Section 2.0 also fully lists the WDM system specifications as taken from the contract statement of work (SOW). Optical test results from coupler fabrication tasks are reported in Section 3.0 while overall system tests are covered in Section 4.0. Conclusions drawn during the contract activities are described in Section 5.0.

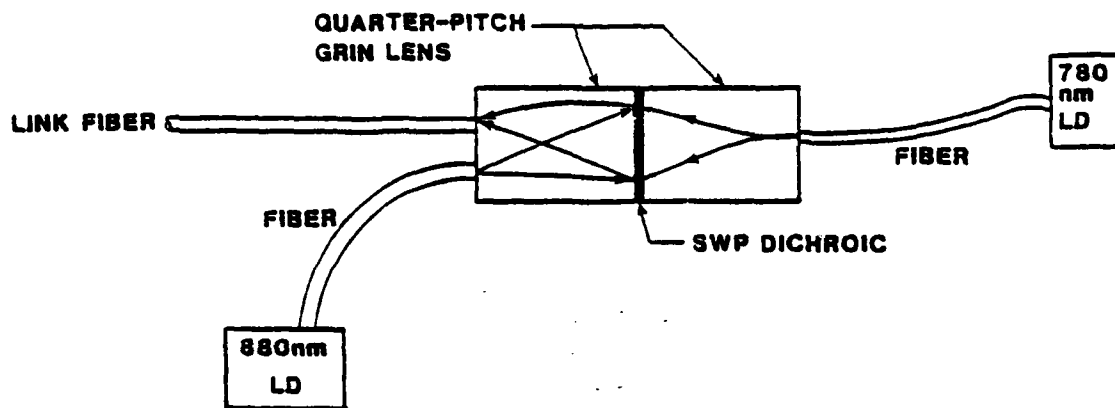
2.0 COUPLER DESIGN

The WDM couplers used for the system were of the lensed dichroic type. They were fabricated using a custom dichroic filter, active fabrication techniques, and single-fiber cable leads. This report section describes the general optical design of the coupler, the coupler package design, and the specifications to which the design was made.

2.1 Lensed Dichroic Coupler (LDC) Design

Figure 2.1-1 illustrates the construction of the multiplex LDC coupler. Wavelength selectivity is controlled by a dichroic filter and collimation/focusing is done with graded-index (GRIN) lenses. The resulting structure has good optical and environmental characteristics. The optical efficiency of the coupler is determined by the imaging characteristics of the GRIN lenses and the performance of the dichroic filter. Crosstalk characteristics are mainly determined by the filter performance.

The two wavelength channels of an LDC coupler are sometimes referred to as the "reflection" channel and the "transmission" channel. This terminology describes the behavior of the optical channels as they interact with the dichroic filter. The filter can be either the "short wavelength pass" (SWP) or the "long wavelength pass" (LWP) type. An SWP filter was used in the 780-nm/880-nm LDC couplers discussed in this report. Distinction between the



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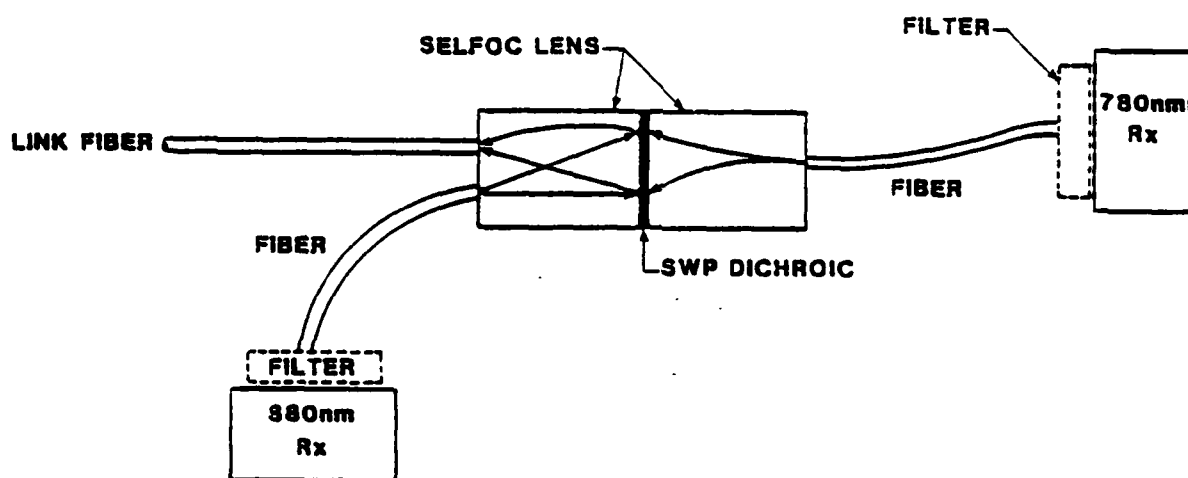
Figure 2.1-1. Lensed Dichroic Multiplex Coupler Design Using a Short Wavelength Pass (SWP) Dichroic Filter. All Fibers Are 50- μm /125- μm Core/Cladding Diameter.

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transmission and reflection channels is important because the reflection channel sometimes requires additional filtering to reduce crosstalk. Figure 2.1-2 illustrates the placement of such a filter in the demultiplex coupler. This filter absorbs short wavelength power but passes the 880-nm channel power. The crosstalk received by the 880-nm detector is thus determined by the combined characteristics of the dichroic filter used in reflection and the transmission of the additional filter. Section 3.0 of this report provides the measured spectral characteristics of the filters actually used in the delivered couplers.

2.2 Coupler Package Design

The package used for the multiplex and demultiplex couplers is shown in Figure 2.2-1. The optical components comprising the LDC were embedded in room temperature vulcanizing (RTV) silicone rubber inside a brass tube with a heat shrink tubing bend limiter on each end. This assembly was then embedded with epoxy in an aluminum housing. This housing protected the coupler and provided strain relief for the single-fiber optical cable leads. Packaging of the couplers was done before crosstalk tests were made, and the necessity of an absorption filter in one of the demultiplexer channels required a separate housing. This absorption filter was packaged within a brass tube installed inline with the cable lead of the affected coupler channel. The absorption filter optical assembly was embedded in RTV within a brass tube. This assembly



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Figure 2.1-2. Optical Demultiplex Coupler Illustrating Placement of Crosstalk-Reducing Absorption Filter in the Reflection Channel. The Link Fiber Is 50- μm /125- μm Core/Cladding Diameter, and the Two Receiver Fibers Are 100 μm /140 μm Core/Cladding Diameter.

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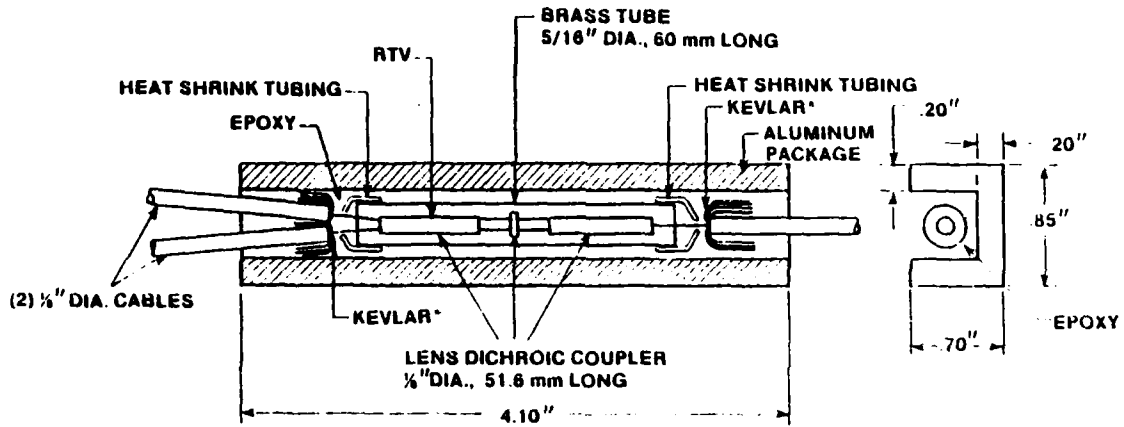
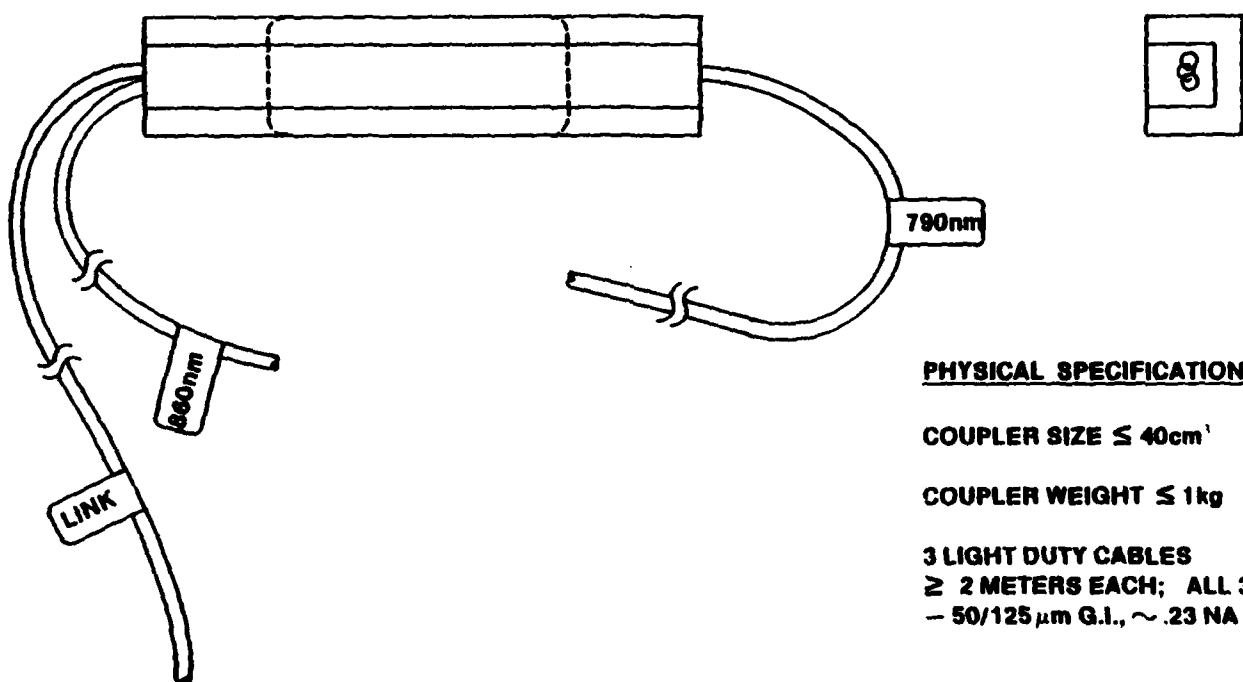


Figure 2.2-1. NRL WDM Coupler and Package.

was then embedded with epoxy in another brass tube, thus providing strain relief for the Kevlar® strength members of the cable.

2.3 System and Coupler Specifications

Figures 2.3-1 and 2.3-2 illustrate the multiplex and demultiplex couplers respectively. These figures also list the physical specifications of the couplers as taken from the contract SOW. Specifications for the couplers connected as a system and for the environmental coupler requirements are listed in Table 2.3-1. Test results on the couplers are covered in Sections 3.0 and 4.0 of this report.



PHYSICAL SPECIFICATIONS

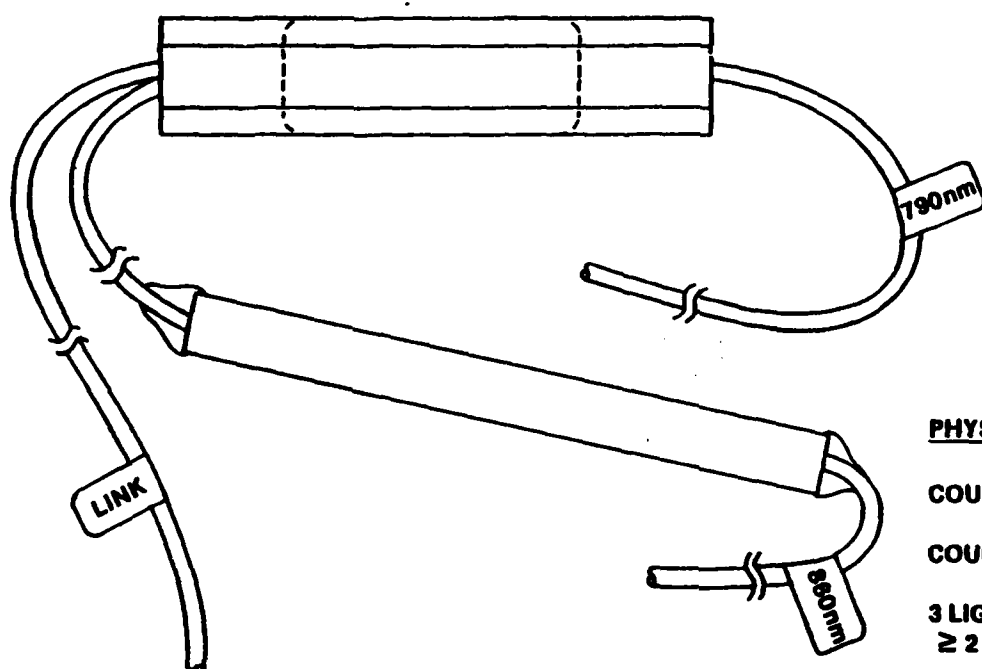
COUPLER SIZE $\leq 40\text{cm}^1$

COUPLER WEIGHT $\leq 1\text{kg}$

**3 LIGHT DUTY CABLES
 ≥ 2 METERS EACH; ALL 3
 - 50/125 μm G.I., $\sim .23$ NA FIBER**

302 16132

Figure 2.3-1. WDM Multiplexer.



PHYSICAL SPECIFICATIONS

COUPLER SIZE $\leq 40\text{cm}^3$

COUPLER WEIGHT $\leq 1\text{kg}$

**3 LIGHT DUTY CABLES
 ≥ 2 METERS EACH**

CABLE MARKED "LINK"
— $50/125\mu\text{m}$ G.I., ~ 23 NA

**OTHER 2 CABLES — $100/140\mu\text{m}$
S.I. FIBER**

302 16111

Figure 2.3-2. WDM Demultiplexer.

Table 2.3-1. Optical Specification for WDM Demultiplexer and Multiplexer Pair at 790 nm/860 nm.

Optical loss	<6 dB (each channel)
Optical crosstalk rejection	>33 dB (each channel)
Optical passband	>10 nm (each channel)
Dispersion	<2 ns (each channel)
Temperature range	0°C to +50°C; tests made at 0°C, +25°C, and +50°C. Multiple measurements of loss will be reported for each unique measurement condition and will include at least three measurements that disagree by no more than 0.5 dB.
Shock and vibration	Capable of surviving a fall from a height of 76 cm onto reinforced concrete without degradation of performance and capable of operation under vibration with maximum acceleration of 5 g along any axis without impairment of performance.

3.0 TEST RESULTS OF OPTICAL COMPONENTS

The optical components used in coupler fabrication and the couplers themselves were tested at various points during the program. This report section contains the results of these tests and a discussion about the influence of test results on coupler construction. In order of discussion, the components covered are injection laser diodes, dichroic filters, couplers, and short wavelength absorption filters.

3.1 Laser Diodes

Nominal channel wavelengths for the system were 780 nm and 880 nm; the actual operation wavelengths were determined by the emission characteristics of the injection laser diodes used. The laser diodes used during the coupler fabrication measurements and the coupler system measurements were a 789-nm laser diode from General Optronics and an 862-nm laser diode made at ITT EOPD. The spectral emission curves for these laser diodes are shown in Figures 3.1-1 and 3.1-2. These waves showed that the diodes were suitable for the coupler testing purposes.

3.2 Coupler Dichroic Filter

The SWP dichroic filter was custom made for this project by Optical Coating Laboratory Incorporated (OCLI). Figure 3.2-1 is OCLI's transmittance versus wavelength curve for the the filter. Transmittance tests made at ITT EOPD showed that the curve had shifted approximately 10 nm toward longer wavelengths. This shift

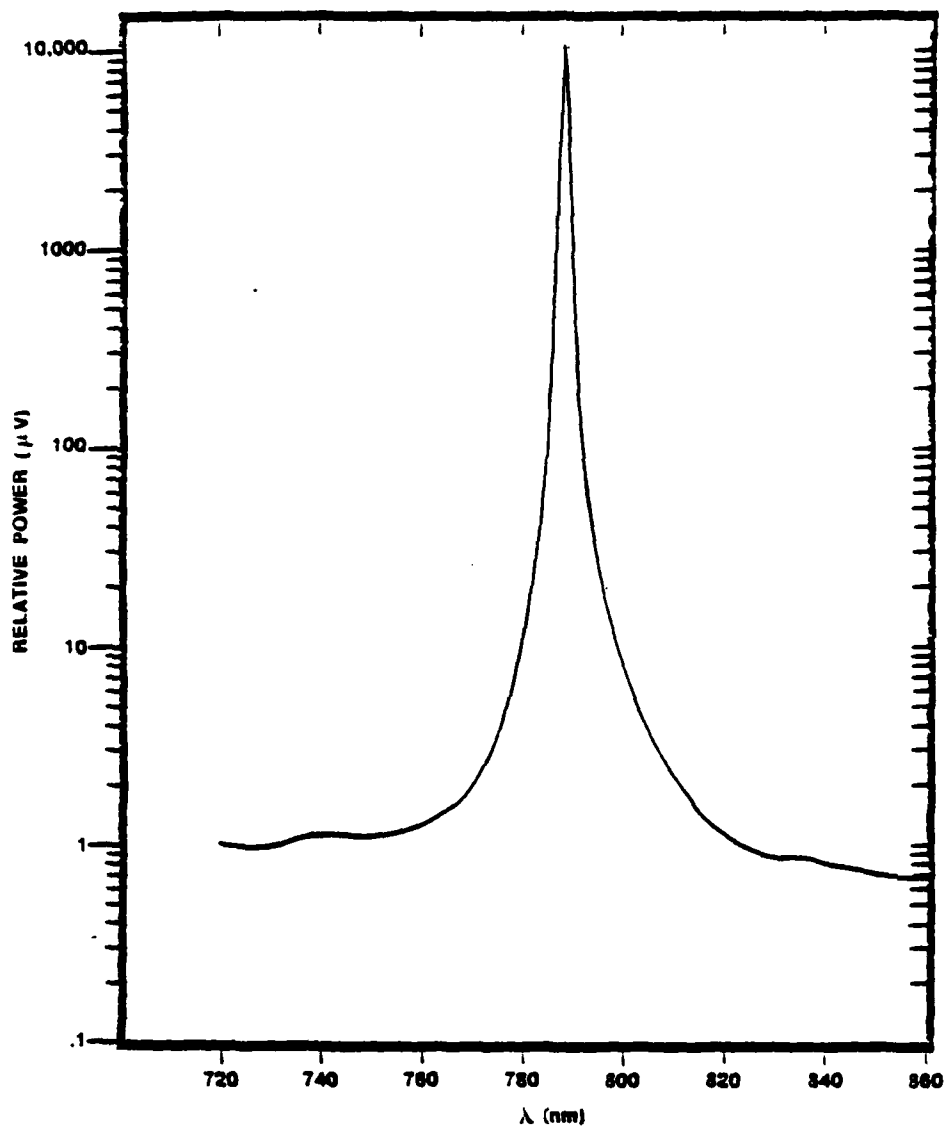


Figure 3.1-1. Relative Power Output of the 790-nm Laser Diode as a Function of Wavelength. Measurements Made With a Scanning Monochromator Set for a Spectral Resolution of ~ 1 nm.

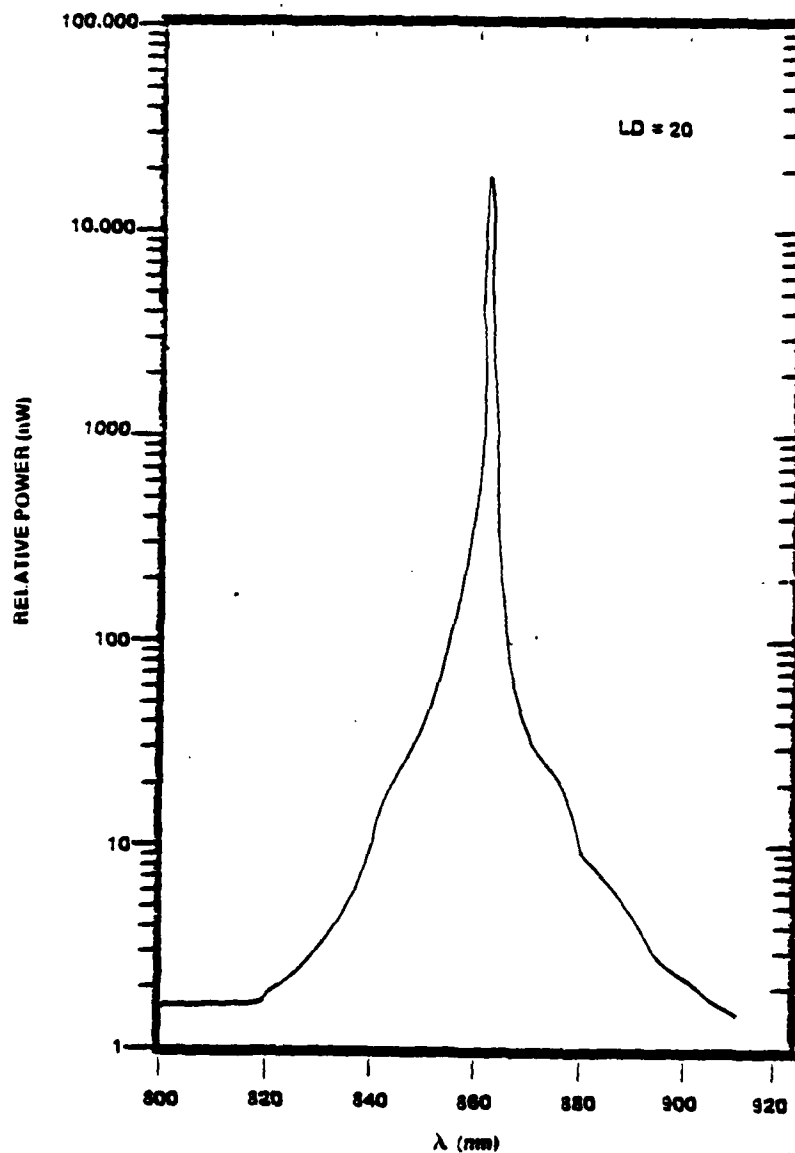
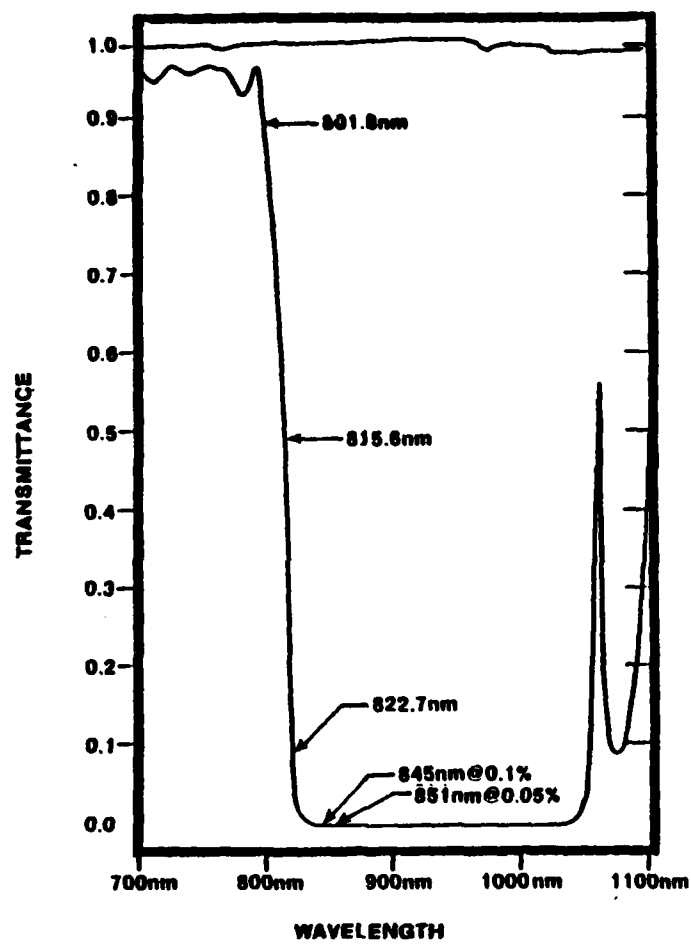


Figure 3.1-2. Relative Power Output of the 860-nm Laser Diode as a Function of Wavelength. Measurements Made With a Scanning Monochromator With a Spectral Resolution of ~1 nm.



102 15400

Figure 3.2-1. Transmittance of Coupler Filter as a Function of Wavelength.

was expected and was due to absorption of humidity by the coating as it reached equilibrium with the environment. No further shifts occur once equilibrium is established. Measurements of the couplers, reported in the next report subsection, showed the filter transmittance characteristics to be satisfactory. Reflectance characteristics of the dichroic were not directly measured, but it can be inferred from Figure 3.2-1 that "some" 780-nm light was reflected by the coating. This reflection was <5% of the incident power but was enough to cause unacceptable crosstalk in the 880-nm channel.

3.3 Initial Coupler Fabrication Results

The multiplex and demultiplex couplers were fabricated independently using the laser diodes described in paragraph 3.1 to inject into the coupler input fiber(s). Coupler output powers were monitored with a large area silicon detector during the epoxy curing procedure. Table 3.3-1 contains the loss and crosstalk data. These data were taken before the additional filter was installed in the demultiplexer 860-nm channel. The need for this filter was indicated by the low crosstalk rejection (17.5 dB) of the 790-nm signal from the 860-nm channel.

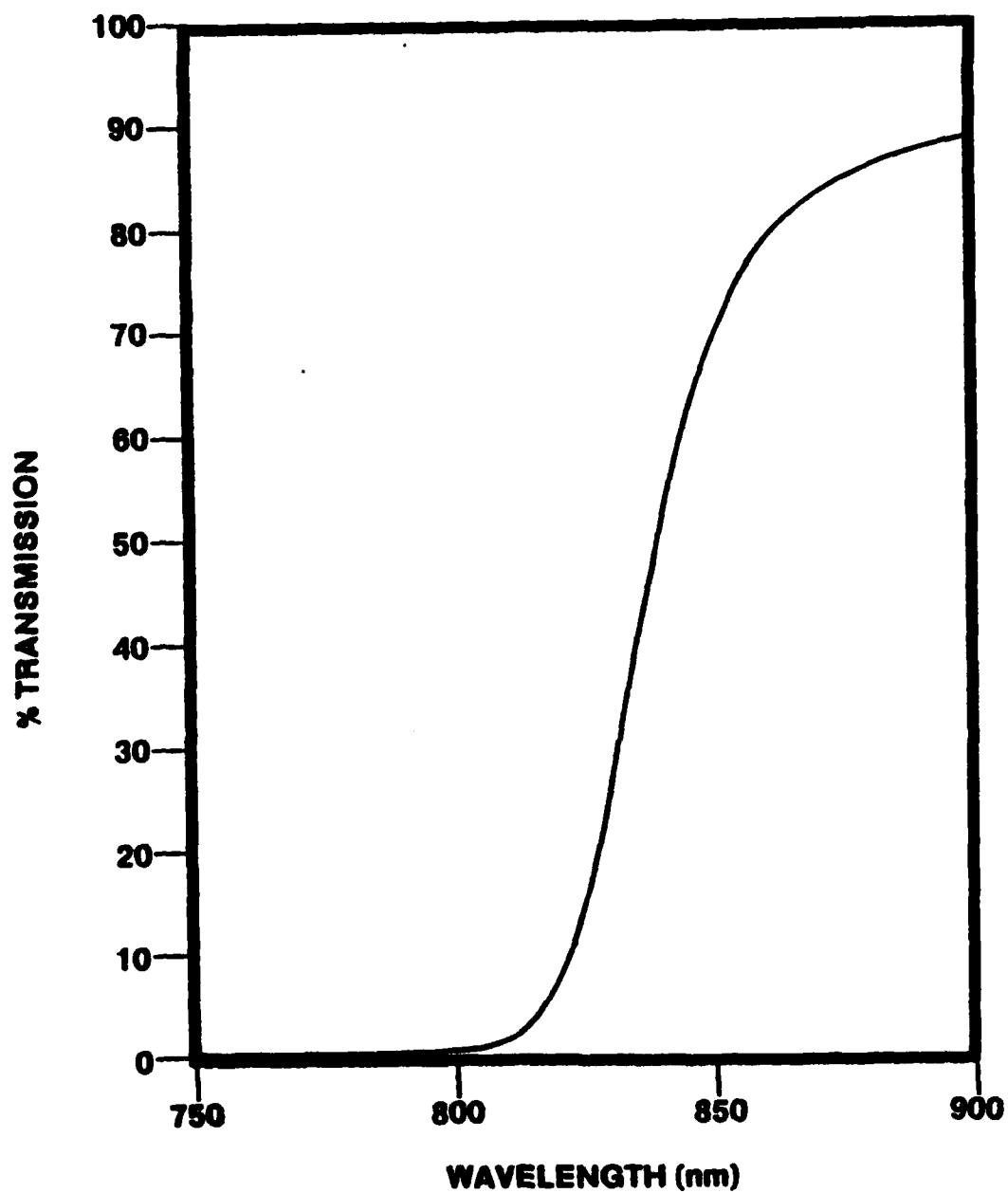
3.4 Short Wavelength Absorption Filter

Preliminary tests of the couplers as a system showed the couplers would meet the specifications with the exception of crosstalk from the 790-nm signal into the 860-nm channel. This problem was

Table 3.3-1. Coupler Initial Fabrication Data.

<u>Coupler</u>	<u>Channel Wavelength (nm)</u>	<u>Optical Loss (dB)</u>	<u>Crosstalk Rejection From Other Wavelengths (dB)</u>
Multiplexer	790	0.5	Not applicable
	860	0.6	Not applicable
Demultiplexer	790	0.4	30.3
	860	0.2	17.5

anticipated in the technical proposal and, if necessary, a GaAs filter was planned for the affected coupler path. However, optical tests showed the purchased GaAs filter was unsatisfactory because it did not transmit the 860-nm channel as planned. A commercially available replacement long wavelength pass absorption filter was ordered to replace the improper GaAs unit. This absorption filter was 1/8 in thick so it had to be installed between two Selfoc® lenses in a structure similar to the coupler design. The "filter coupler" was packaged slightly differently from the original coupler and is described in paragraph 2.2. Figure 3.4-1 is the transmission curve of the filter used in the couplers.



102 16220

Figure 3.4-1. Transmission Curve of Absorption Filter.

4.0 OPTICAL TESTS OF COUPLER SYSTEM

4.1 Coupler System Test Methodology

The optical specifications for the WDM couplers were for the couplers connected as a system with a long (~1 km) fiber link between them. Figure 4.1-1 is a diagram of the test system. The laser diodes were fusion spliced to the appropriate inputs of the multiplexer. The multiplexer link fiber and the demultiplexer link fiber were fusion spliced to a 900-m spool of 50- μ m/125- μ m graded-index fiber.

As the system was being spliced together, the loss of the 900-m link fiber was measured for both wavelengths. This fiber loss was later subtracted from the coupler system loss since the link fiber loss was not a part of coupler losses. The link fiber was needed for these measurements because demultiplexer loss could be dependent on injection conditions. The fiber link provided an equilibrium injection condition for the demultiplex coupler.

The laser diode sources were driven by a circuit which modulated the stimulated emission of the devices at a known frequency. Detector outputs were monitored with a lock-in amplifier which received a reference signal from the laser driver. Dynamic range was in excess of 50 dB and was sufficient for both loss and cross-talk measurements.

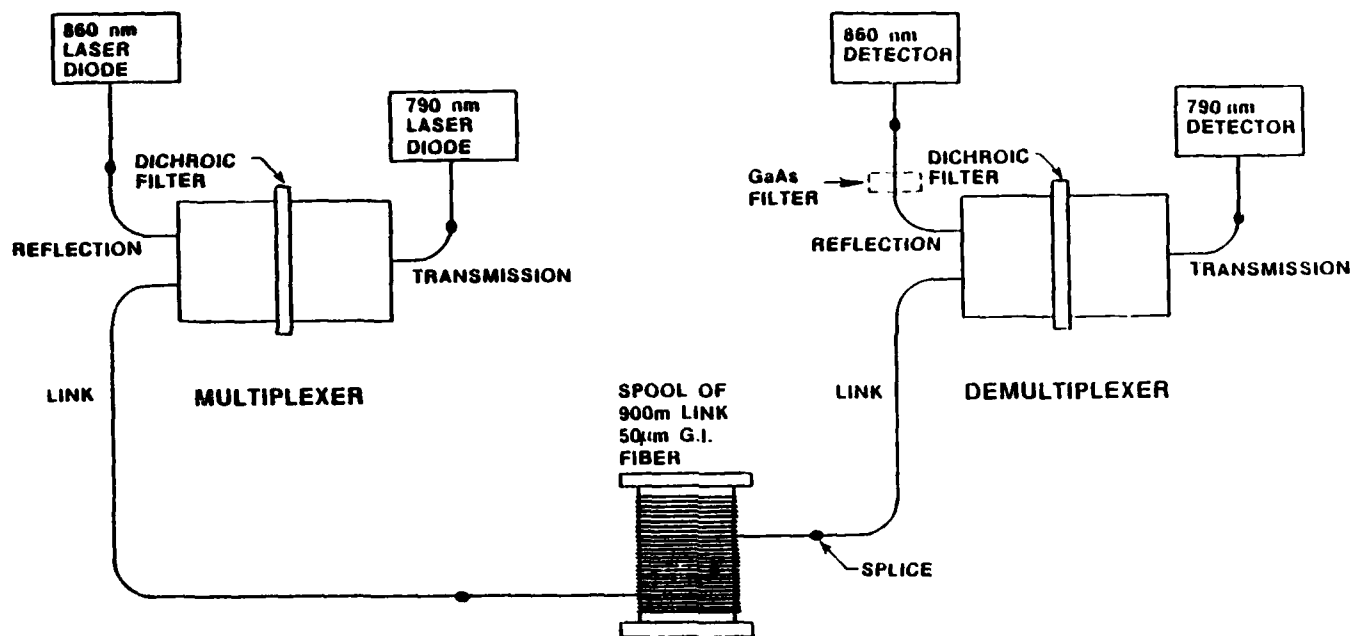


Figure 4.1-1. WDM Multiplexing System.

4.2 Optical Passband

The optical passband as determined by measurements at 790 nm, 860 nm, and information from Figure 3.2-1 was as follows:

- 790 nm channel - 100 nm
(700 to 800 nm)
- 860 nm channel - 150 nm
(850 to 1000 nm)

4.3 Dispersion of Coupler Pair at 850 nm in 860-nm Channel

Dispersion measurements were made at 850 nm using standard ITT EOPD procedures normally used for fiber measurements. The following results were achieved:

- Full width half maximum dispersion: <0.43 ns
- 10% dispersion <1.29 ns

The dispersion was calculated using the following equation:

$$\tau = \sqrt{(\tau_T^2 - \tau_S^2) - (\tau_F^2 - \tau_S^2)} \quad (4-1)$$

where

τ_T = total dispersion of coupler system

τ_F = dispersion of fiber link

τ_S = system response

τ = dispersion of coupler pair

These results are well below the 2.00 ns requirement and most likely reflect measurement system limits rather than actual coupler characteristics.

4.4 Temperature Tests of Coupler System

The multiplex and the demultiplex couplers were placed in a calibrated temperature chamber, leaving the link fiber spool, the fusion splices, the laser diodes, the detectors, and the electronic equipment outside of the chamber. The couplers were heated from +25°C to +50°C for 2 h, cooled to 0°C for 2 h, then heated back to +25°C. Multiple measurements at 30-min intervals were made at each temperature. Table 4.4-1 contains the results.

4.5 Shock Test of Coupler Pair

A pair of couplers similar to the deliverables was dropped from a height of 76 cm onto reinforced concrete. A continuity test was performed after the shock test; this demonstrated that each channel still transmitted as required. The test was not performed on the deliverable units to eliminate any risk of damage and a consequent requirement for additional funds.

4.6 Vibration Test of Coupler Pair

Vibration testing was performed per paragraph 4.2, Procedure I, of MIL-T-5422F(AS), with the vibration level per curve IIIA on Figure 6 of the procedure, where the maximum acceleration is 5 g. This

Table 4.4-1. Temperature Test Data for Coupler Pair.

Temperature (°C)	860 nm Channel		790 nm Channel	
	Optical Loss (dB)	Crosstalk Rejection (dB)	Optical Loss (dB)	Crosstalk Rejection (dB)
25	3.7 ±0.5	51 ±1	2.6 ±0.5	33 ±1
25	3.7	49	2.6	33
50	4.0	50	1.9	33
50	4.0	50	2.2	33
50	4.0	51	2.0	33
50	4.1	51	2.2	33
0	2.3	48	2.4	32*
0	2.2	48	2.8	32*
0	2.2	48	2.8	32*
0	2.2	48	2.9	32*
25	3.7	50	2.4	33
25	3.8	50	2.4	33
25	3.8	50	2.3	33

*Indicates value not meeting requirements.

test was done along each axis with a continuity test performed after each portion of the test. The coupler pair was then fully tested; the results are shown in Table 4.6-1. These results agree, within measurement error, with the tests done previously, as shown in Table 4.4-1. The vibration test was done on the actual deliverable coupler set.

Table 4.6-1. Final Data for Multiplexer and Demultiplexer Combined. Tests Done at 25°C.

<u>Channel Wavelength</u>	<u>Optical Loss</u>	<u>Crosstalk Rejection From Other Wavelength</u>
860 nm	4.4 \pm 0.5 dB	51 \pm 1 dB
790 nm	3.0 \pm 0.5 dB	33 \pm 1 dB

Note: The throughput measurements errors consist of \pm 0.3 dB for three splices and \pm 0.2 dB for the sub-tracted link fiber loss. The crosstalk measurements errors have an additional \pm 0.5 dB due to noise levels in the measurement equipment.

5.0 CONCLUSION

A wavelength division multiplexing system consisting of two lensed dichroic couplers which provided codirectional channels at 780-nm and 880-nm wavelengths was designed, fabricated, and tested. The couplers were tested as a system using laser diode sources with peak emission power at 790 nm and 860 nm. For the system composed of the multiplex coupler, a 900-m fiber link, and the demultiplex coupler, maximum coupler channel loss was measured to be 4.1 dB over the 0°C to +50°C required range. This low loss was well within the 6.0 dB requirement and essentially met the 4.0 dB contract goal. Over the same temperature range, crosstalk rejection was about 50 dB in the 860-nm channel and 33 dB in the 790-nm channel. Pulse dispersion was well below the 2.0 ns maximum requirement.

The couplers passed environmental tests including 0°C to +50°C temperature, vibration per MIL-T-5422F(AS), and an NRL-specified shock test. Coupler mechanical design featured compact housings and fiber optic leads of light-duty, single-fiber cable. The deliverable couplers were equipped with a separately housed absorption filter which reduced crosstalk in the 860-nm channel to an acceptable level. This filter could be integrated into the coupler housing in future units to provide a very compact, high performance component for WDM system use.

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